Columbia Hills, Gusev Crater	Location (lat,lon):	**14.5478 S, 175.6255 E** **MOLA128: -1.932 km**

Summary of observations and interpreted history, including unknowns:

Gusev crater formed around 3.9–4.1 billion years ago (Werner et al., 2008). The Columbia Hills may represent peak ring hills, intersecting rims of multiple craters, or eroded, possibly lacustrine fill. Subsequent geologic processes emplaced successive volcanics and possibly evaporites, draping over the Hills at dips of 7–30 degrees (McSween et al., 2008; McCoy et al., 2008; Ruff et al., 2014). Basaltic plains dated to 3.65 Ga onlap the Columbia Hills (Greeley et al., 2005). Multiple igneous rock units are present in the Columbia Hills, including high-alkali and high olivine materials and some tuffs or ashes (McSween et al., 2008). Several types of evidence of aqueous processes are preserved in rocks that have possible Al-phyllosilicates (Clark et al., 2007), Mg-Fe carbonates (Morris et al., 2010), and opaline silica (Squyres et al., 2008; Ruff et al., 2011). Near surface soil crusts have ferric sulfates, calcium sulfates, and silica (Arvidson et al., 2010). The silica-enriched rocks and ferric sulfate-bearing soils occur in and around the 80 m-diameter “Home Plate” volcaniclastic deposit. The presence of the Spirit rover represents a long duration exposure facility experiment, of potential value in human exploration.

Key units are: the "Comanche" carbonate-bearing outcrops (~15-30 wt% Mg-Fe carbonate, plus olivine and an amorphous silicate), which has been interpreted to result from (a) hydrothermal alteration (Morris et al., 2010) or (b) evaporation of an ephemeral lake (Ruff et al., 2014). The 50–90% silica rocks with digitate morphology may represent (a) leached basaltic materials or (b) hot spring deposits (see Squyres et al., 2008; Ruff et al., 2011 for multiple hypotheses). In each case, (b) might be relatively more favorable for biosignature preservation. Extensive plains lava flows represent a dateable unit for constraining crater retention age.

Summary of key investigations

1. Investigate and sample siliceous deposits discovered by the Spirit rover on the east side of the “Home Plate” feature, and candidate deposits not visited by Spirit to the west and south of Home Plate. These deposits have been compared (Ruff and Farmer, 2016) on the basis of their morphology and mineralogy to hot spring sinter deposits known to support microbial life on Earth, and have thus been called potential biosignatures. An alternative hypothesis is that these deposits represent fumarolic acid-sulfate leaching.
2. Investigate and sample carbonate-bearing outcrops discovered by the Spirit rover at “Comanche”.
3. Investigate and sample Adirondack Class basalt widely distributed about the floor of Gusev Crater.
4. Investigate rocks in outcrop and float along the north slope of Husband Hill determined by Spirit to show evidence of aqueous alteration.
5. Investigate the area imaged, but not visited by Spirit known as the “Promised Land”. CRISM data suggest carbonates are present there in a unit that predates basalt on the crater floor.

Cognizant Individuals/Advocates:

Steve Ruff, Jim Rice

Link to JMARS session file | Link to Workshop 2 rubric summary

TBD

Key Publications list (grouped by topic):

Arvidson, R. E., et al. (2008), Spirit Mars Rover Mission to the Columbia Hills, Gusev Crater: Mission overview and selected results from the Cumberland Ridge to Home Plate, J. Geophys. Res., 113, E12S33, doi:10.1029/2008JE003183.

Arvidson, R. E., et al. (2010), Spirit Mars Rover Mission: Overview and selected results from the northern Home Plate Winter Haven to the side of Scamander crater, J. Geophys. Res., 115, E00F03, doi:10.1029/2010JE003633.

Carter, J., Poulet, F. (2012) Orbital identification of clays and carbonates in Gusev crater, Icarus, 219, 250-253, doi:10.1016/j.icarus.2012.02.024.

Greeley, R., et al. (2005) Fluid lava flows in Gusev crater, Mars: JGR 110, E05008, doi:10.1029/2005JE002401.

Lewis, K. W., et al. (2008), Structure and stratigraphy of Home Plate from the Spirit Mars Exploration Rover, J. Geophys. Res., 113, E12S36, doi:10.1029/2007JE003025.

McCoy, T. J., et al. (2008), Structure, stratigraphy, and origin of Husband Hill, Columbia Hills, Gusev Crater, Mars, J. Geophys. Res., 113, E06S03, doi:10.1029/2007JE003041.

McSween, H. Y., et al. (2008), Mineralogy of volcanic rocks in Gusev Crater, Mars: Reconciling Moessbauer, Alpha Particle X-Ray Spectrometer, and Miniature Thermal Emission Spectrometer spectra, J. Geophys. Res., 113, E06S04, doi:10.1029/2007JE002970.

Ming, D. W., et al. (2006), Geochemical and mineralogical indicators for aqueous processes in the Columbia Hills of Gusev
crater, Mars, J. Geophys. Res., 111, E02S12, doi:10.1029/2005JE002560.

Morris, R.V., et al. (2010) Identification of carbonate-rich outcrops on Mars by the Spirit rover: Science, v. 329, p. 421–424, doi:10.1126/science.1189667.

Ruff, S. et al. (2014) Evidence for a Noachian-aged ephemeral lake in Gusev crater, Mars, Geology, 42, 359-362

Ruff, S. et al. (2011) Characteristics, distribution, origin, and significance of opaline silica observed by the Spirit rover in Gusev crater, Mars, JGR, 116, E00F23, doi:10.1029/2010JE003767.

Ruff, S. and and Farmer, J. (2016) Silica deposits on Mars with features resembling hot spring biosignatures at El Tatio in Chile, Nature Communications, 7, 13554, doi:10.1038/ncomms13554.

Squyres, S. W., et al (2008), Detection of silica- rich deposits on Mars, Science, 320, 1063–1067, doi:10.1126/science.1155429.

Regional Context Figure (ref: Irwin et al. 2004)

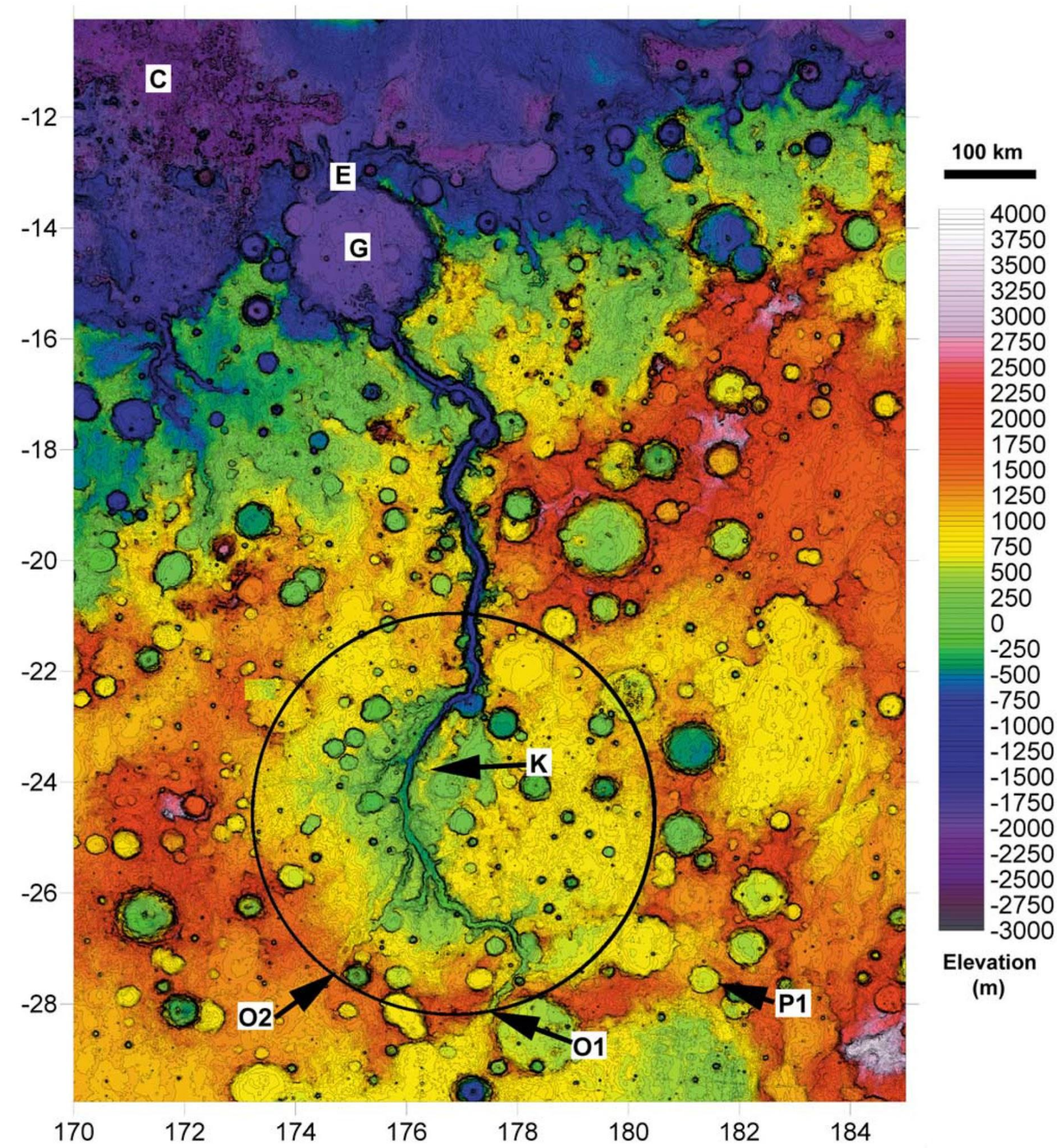
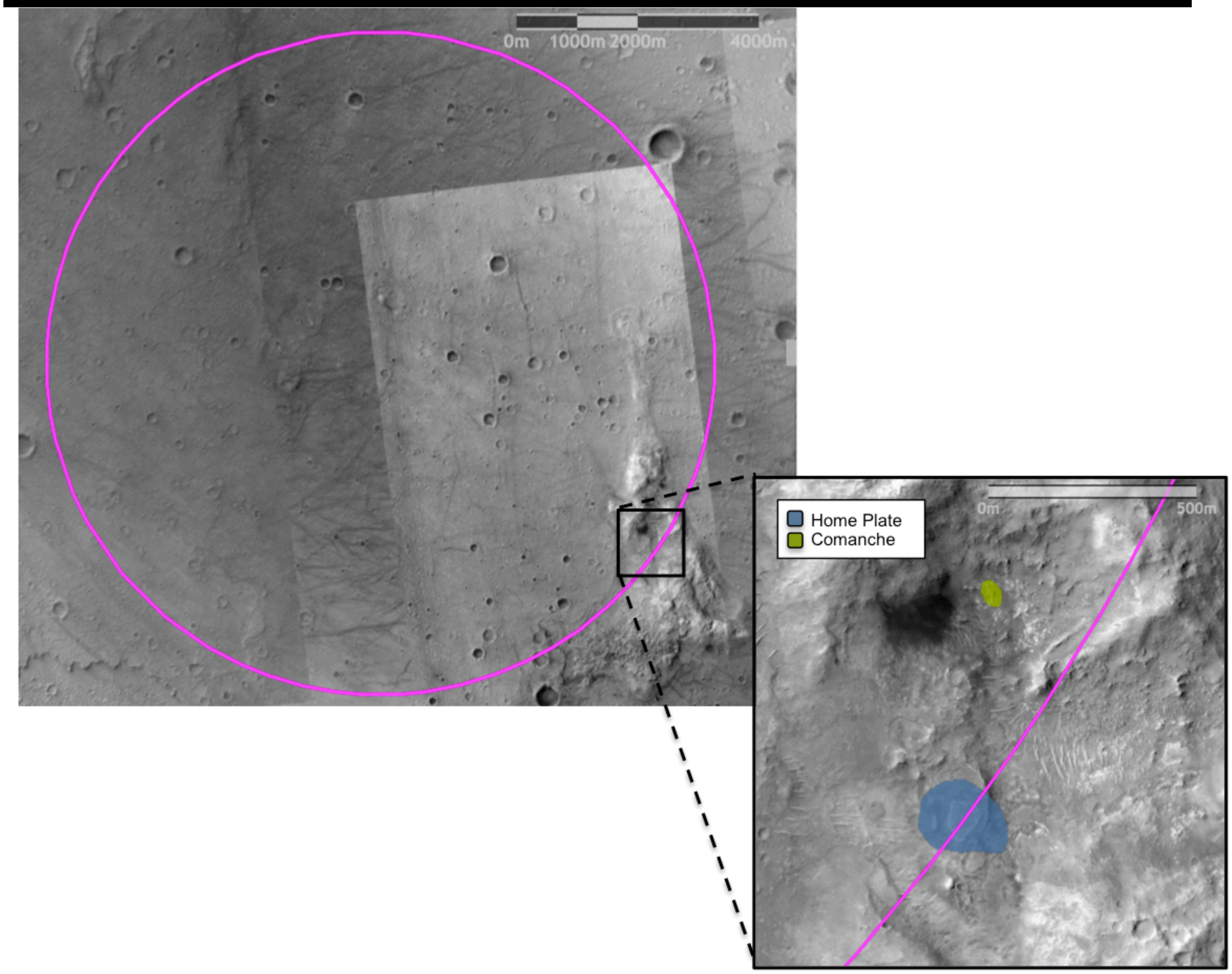


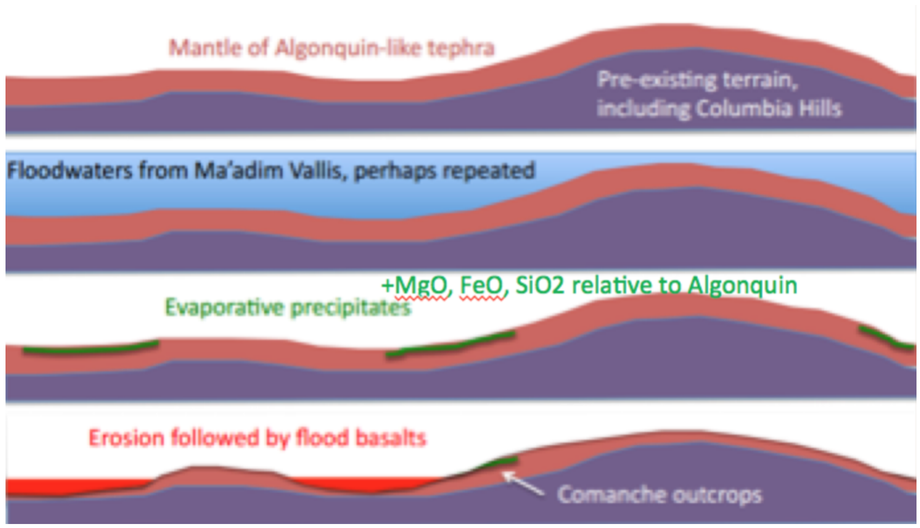
Figure 1. Ma'adim Vallis in a cylindrical projection of MOLA topography (128 pixel/degree, 50 m contour interval). The valley crosscuts a circular, highly degraded impact basin (black circle), identified as the intermediate basin. The locations of the knickpoint (K), Gusev crater (G), the Gusev exit breach (E), and chaotic terrain north of the valley terminus (C) are indicated. The lower reach of the valley lies north of the knickpoint, the intermediate reach extends along the rest of the intermediate basin floor, and the upper reach occurs along its southern interior slope. Ma'adim Vallis originates full-born at two source spillways (O1 and O2) in the intermediate basin divide. Another low point (P1) contains a degraded crater, the rim of which may have formerly raised the divide above the 1250 m level of O2.

Ellipse ROI Map or Geologic Map Figure



(ellipse is ~12 km wide)

Regional (~3x ellipse) Stratigraphic Column Figure (ref: Ruff et al. 2014; Lewis et al. 2008)



Interpretive stratigraphic evolution of Columbia Hills, scenario presented by Ruff et al. (2014). An alternative scenario has Comanche carbonates forming as a result of high temperature (hydrothermal) precipitation associated with local volcanism (Morris et al. 2010).

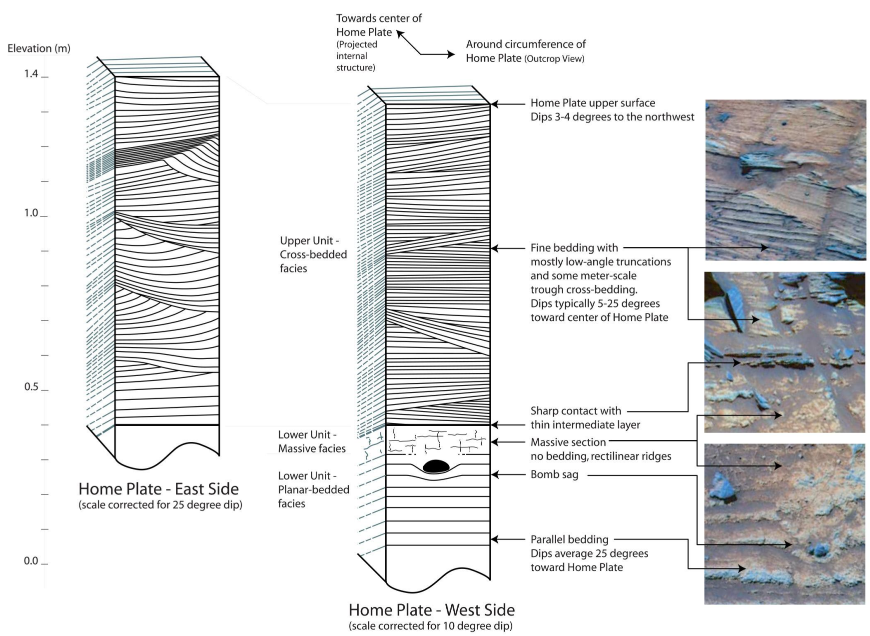


Figure 2. Stratigraphic column of Home Plate outcrops, with representative examples. The primary division is between the lower unit, where planar bedded and massive facies are observed, and the upper unit, dominated by cross stratification. The presence of a putative bomb sag in the lower unit points to an explosive volcanic origin for the Home Plate sediment. On the east side of Home Plate, the lower unit has not been identified, although a correlation is indicated between a prominent layer seen at the base of the upper unit at both locations. After correcting for the average structural dip on both the west and east sides of Home Plate, the stratigraphic thickness of the upper unit is calculated to be similar to within 10 cm between outcrops. The side panel of each column indicates the projected internal structure, which dips toward the center of Home Plate at each location visited by Spirit. Examples of each unit are indicated to the right. Each image on the right is a Pancam false color stretch using filters L2, L5, and L7 (753, 535, and 432 nm, respectively). Image numbers are (top) 2P228456914EFFAS6MP2440L2M1; (middle) 2P192944022EFFAO55P2275L2M1; and (bottom) 2P193032914EF-FAO55P2276L2M1.

From Lewis et al. 2008 (JGR)

Inferred Timeline

3.9-4.1 Ga: Gusev crater forms (Werner, 2008)
Columbia Hills topography formed as a result of Gusev central peak or mutual interference of overlapping crater rims (McCoy et al. 2008).
Volcaniclastic deposition of olivine-rich tephra as Algonquin outcrops, subsequently altered by carbonate- and silica-bearing (?) fluids.
Carbonate deposition in Comanche outcrops initially interpreted to have resulted from direct precipitation under hydrothermal conditions (Morris et al. 2010). Later interpretation and comparison with ALH84001 carbonates suggests low temperature, evaporitic precipitation (Ruff et al. 2014).
Flooding from Ma'Adim Vallis led to fluvio-lacustrine deposition of Fe/Mg clays (and carbonates?) (Carter and Poulet 2012) during Noachian-Hesperian time.
3.65 Ga: Basaltic Plains emplaced, embaying Columbia Hills (Greeley et al., 2005).

Summary of Top 3-5 Units/ROIs

ROI	Aqueous or Igneous?	Environmental settings for biosignature preservation	Aqueous geochemical environments indicated by mineral assemblages
1. Home Plate	Aqueous	possible hot spring	opaline silica may indicate deposition as sinter
2. Comanche Carbonates	Aqueous	volcanic hydrothermal or lacustrine	Fe- Mg-carbonates indicate hydrothermal or evaporitic deposition
3. Plains Basalt	Igneous	N/A	
4. Promised Land	Aqueous	lacustrine?	Possible carbonates predating Plains Basalt

Top 3-5 Units/ROIs Detailed Descriptions

Unit/ROI Name:	Home Plate silica deposits
Aqueous and/or Igneous?	Aqueous

Description: Opaline silica occurring in nodular, sometimes digitate masses with stratiform expression overlying platy "Halley Subclass" interpreted as altered ash (Ruff and Farmer 2016 and references therein).

Interpretation(s):

- High (up to 91 wt.%) SiO_2 content and association with volcanic units interpreted to indicate a hydrothermal origin (Squyres et al. 2008). Most recently interpreted on the basis of morphology and spectral similarity to be analogous to hydrothermal spring deposits at El Tatio, Chile (Ruff and Farmer 2016).
- Alternative interpretations include fumarolic acid-sulfate leaching.

In Situ Investigations:

- Mastcam-Z, WATSON, SuperCam RMI imaging to document m-scale context to sub-mm morphology. Attempt to distinguish leaching textures from primary hydrothermal spring textures (test sinter hypothesis).
- WATSON to look for sub-mm scale layering in digitate structures (e.g. consistent with microstromatolites)
- PIXL mapping to seek morphologically correlated minor element compositions
- SHERLOC mapping to seek organics and or secondary minerals associated with opaline silica
- RIMFAX to assess subsurface expression of Home Plate Si deposits and contact with underlying Halley Subclass unit

Returned Sample Analyses:

- Light and electron microscopy to seek microfossils and/or mat textures
- Bulk and spatially resolved
  - organic geochemistry to seek molecular fossils
  - inorganic geochemistry to seek micro- to nano-scale concentrations of biologically important elements

- isotope geochemistry to seek possible metabolic fractionation of Si, O, C, Zn, Cr isotopes

Unit/ROI Name:	Comanche outcrops
Aqueous and/or Igneous?	Aqueous and igneous
Description: Mg-Fe carbonates (16-34%) associated with (~40%) Mg-rich olivine, with remainder as amorphous silicate. Bedded, conforming to local topography. Surface texture of carbonates initially described as “granular” relative to “massive” texture of associated olivine-rich volcaniclastics (Morris et al. 2010), although this distinction was later interpreted to be confined to weathered surfaces (Ruff et al. 2014).	
Interpretation(s):	
• Algonquin interpreted as volcaniclastic tephra • Comanche carbonates initially interpreted to have precipitated under hydrothermal conditions (Morris et al. 2010), and later to have precipitated at low temperatures, possibly as lacustrine evaporites (Ruff et al. 2014).	
In Situ Investigations:	
• Attempt to distinguish hydrothermal (high T) vs. evaporitic (low T) depositional models for Comanche carbonates. • Mastcam-Z, WATSON, SuperCam RMI imaging to document m-scale context to sub-mm textures. Distinguish weathering from primary textures. • PIXL mapping to seek morphologically correlated minor element compositions • SHERLOC mapping to seek organics and/or alteration minerals • RIMFAX to assess structural relations between Algonquin and Comanche outcrops	
Returned Sample Analyses:	

- Light and electron microscopy for basic petrology and to seek microfossils and/or mat textures
- Bulk and spatially resolved
  - organic geochemistry to seek molecular fossils
  - inorganic geochemistry to seek micro- to nano-scale concentrations of biologically important elements
  - isotope geochemistry to seek possible metabolic fractionation of Si, O, C, Mg, Fe, isotopes; clumped isotopes to assess formation temperatures

Unit/ROI Name:	Plains Basalt
Aqueous and/or Igneous?	Igneous
Description:	
Adirondack-class basalts -- fine grained, containing ferroan olivine (~Fo60) megacrysts, irregular vesicles and vugs	
Interpretation(s):	
• Hesperian-age basaltic lava flow • primary, mantle-derived melts (McSween et al. 2006)	
In Situ Investigations:	
• Mastcam-Z, WATSON, SuperCam RMI imaging to document m-scale structural context to sub-mm textures. Distinguish weathering textures from primary igneous textures. • SuperCam to determine igneous mineralogy • SuperCam LIBS and PIXL mapping for mm- to sub-mm scale elemental composition • RIMFAX to assess structural relations between Plains Basalts and possible underlying carbonate units at Promised Land	
Returned Sample Analyses:	
• classical igneous petrology • geochronology • isotope geochemistry to understand planetary evolution	

Biosignatures (M2020 Objective B and Objective C + e2e-iSAG Type 1A, 1B samples)

Biosignature Category	Inferred Location at Site	Biosignature Formation & Preservation Potential
Organic materials	Home Plate and Comanche	Entombed in silica precipitates, intracrystalline organics in carbonates, at carbonate grain boundaries, refractory organics in olivine?
Chemical	Home Plate and Comanche	Morphologically correlated concentrations of minor elements including Mg, Fe, Cr, Zn
Isotopic	Home Plate and Comanche	Si, O, C, S, N(?), Mg, Fe, Cr, Zn isotopes
Mineralogical	Home Plate and Comanche	Opaline silica and carbonates
Micro-morphological	Home Plate and Comanche	Microfossils or microscopic mat textures preserved in silica or carbonates
Macro-morphological	Home Plate and Comanche	Hypothesis that digitate forms may be related to presence of microbes; mat textures in possibly evaporitic carbonates

Dateable Unit(s) for Cratering Chronology Establishment

Unit Name	Total Area (km^2)	Time Period	Geologic Interpretation and uncertainties	What constraints would the unit provide on crater chronology?
Plains basalt	>3500	Early Hesp.	Plains unit with wrinkle ridges; in situ Adirondack basalts.	Dated by Greeley et al., 2005 to 3.65 Ga. Direct constraint from sample of lava

Key Uncertainties/Unknowns about the Site

List the most important uncertainties, unknowns or potential drawbacks about the site

- To what extent do materials accessible represent lake sediments vs. other geologic processes?
  - If evaporite carbonate-rich lake, then preserves alkaline body of water in mid Noachian to early Hesperian
  - If carbonates are instead hydrothermal, then indicate processes related to ground water in mid Noachian to early Hesperian
- To what extent are the forms and structure of silica-rich rocks uniquely indicative of (a) hydrothermal sinter and/or (b) biologically-mediated deposits?
  - For many “bio-suggestive” morphologies observed on Earth, the influence of biology is a possible interpretation, but not a requirement. At a minimum, tests of biogenicity require a demonstration that a biologic influence for a set of observed features is more parsimonious than any abiotic formation mechanism. This must include establishment of robust geologic context consistent with the presence of life as well as multiple, converging lines of evidence supporting biogenicity.
- To what extent can the context and timing of events in the Columbia Hills to relate to events elsewhere on Mars?
  - Timing constraint is post-Gusev (<4.1 Ga) and pre-Adirondack plains basalt (>3.65Ga)
  - Stratigraphy is small-scale and cannot be further correlated in time with other globally significant units. If returned, samples could provide absolute dates of different units
- To what extent can Mars2020, with its in situ package of instruments, learn more than MER Spirit vs. science advances waiting for the return of samples?
  - MER: in-situ chemistry (major, minor); IR emission spectroscopy for silicates, carbonates, sulfates; microscopic imaging; Fe-oxidation state
  - Mars2020: in-situ chemistry (major, minor, trace); IR VSWIR and Raman spectroscopy for silicates, carbonates, sulfates and orgnanics. M2020 would likely provide superior mineral discrimination within class; small-scale petrologic relationships; subsurface stratigraphy, and capability for organics detection.